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Tool Materials Rapid Selection Based on Initial Wear

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Abstract

Based on a large amount of literature about tool wear research, 873 tool wear curves are taken as samples, and statistical analysis is carried out to select the most suitable tool from all the tool materials suggested by the tool manufacturers. Statistical relationships between the initial wear and uniform wear periods are obtained. The results show that there is qualitative relationship between wear rate during initial wear period (WRIWP) and wear rate in uniform wear period (WRUWP) to certain extent. On this basis, a tool material rapid selection method based on the initial wear is put forward, and suitable tool materials for machining titanium alloy are selected. The experimental results indicate that this method is effective and useful. The new tool materials rapid selection can be used to select suitable cutting tool materials quickly before carrying out systematic machinability tests with the most suitable tool materials. The technology can be applied to doing the initial selection of cutting tool materials in either the machinability research or the workshop production.

Key words: metal cutting; tool materials rapid selection; statistic methods; cutting tools; tool wear; tool initial wear

1. Introduction

Progress of aviation industry calls for aircraft parts working reliably under highly stressed and dynamically loaded conditions. As a result, high performance materials are increasingly used in aeronautical area, e.g., high temperature alloys and titanium alloys for airplane engines, high strength steels for aircraft landing gears, composites for aerofoil, aircraft fuselage and so on. The high performance materials usually lead to technical problems such as serious tool wear, low machining efficiency, high production cost, etc. Development of newer and better cutting tool materials is the key to cope with the latest high performance materials. For a certain workpiece to be machined, there are usually tens or even hundreds choices of tool materials suggested by various tool suppliers. For instance, in machining titanium alloy, there are more than fifty tool materials available on the tool market supplied by a dozen cutter manufacturers worldwide. It is usually necessary to select one or two most suitable tool materials via cutting experiments. But cutting tests need great investment and consume large amounts of time, therefore the systematic experimental selection of tool materials based on standard machinability tests is not practical for both laboratory research and workshop production.

Tool life is an important criterion for tool materials selection. It is essential to consider the tool wear in machining aircraft difficult to cut materials. Unfortunately the knowledge about tool wear is not sufficient to predict tool wear via calculation or simulation because of the complexity of the problem, and tool wear study is heavily dependent on experiments. Tool wear tests are time-consuming and expensive. Many researchers[1-3] designed rapid tool wear tests to save time and money, but the mechanism, reliability and applicability of these methods remain to be studied. It was found from experiments that, in general, the higher the wear rate during initial wear period (WRIWP) of tools is, the shorter the tool life would be. There might be certain qualitative relationship between the initial wear and uniform wear periods. If it is true to a certain extent, suitable cutting tool materials could be selected rapidly just through tool initial wear experiments without great consumption of time, material and money. To conduct further research on this relationship, statistical analysis is carried out based on a large amount of literature about tool wear in this article, and a tool materials rapid selection method based on the initial wear is put forward.

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2. Statistical Analysis

A typical tool wear process can be expressed with curve of a tool wear versus cutting time shown in Fig.1, where T and VB_T are tool life and tool wear criteria. When the cutting time is from 0 to T_0, the tool is in its initial wear period and the wear develops faster than that in the uniform wear period which starts at T_0. VB_0 is the flank wear at the end of the initial wear stage. T_0 and VB_0 can be obtained from the wear figures as follows: The first measuring point or the inflection point where the initial wear period finishes and the uniform wear period begin can be regarded as the end of the initial wear period. T_1, VB_1, K_0, K_1, K and g can be calculated with the following equations:

$$T_1 = T - T_0 \tag{1}$$

$$VB_1 = VB_T - VB_0 \tag{2}$$

$$K_0 = VB_0 / T_0 \tag{3}$$

$$K_1 = VB_1 / T_1 \tag{4}$$

$$K = K_0 / K_1 \tag{5}$$

$$g = T_1 / T \tag{6}$$

where T_1 and VB_1 are the cutting time and flank wear for the uniform wear stage respectively, K_1 is the wear rate in uniform wear period (WRUWP), K_0 is WRIWP. Similar treatment can be done for VB_{max}, VC, VC_{max}, VN, KB, KT, KM, etc.

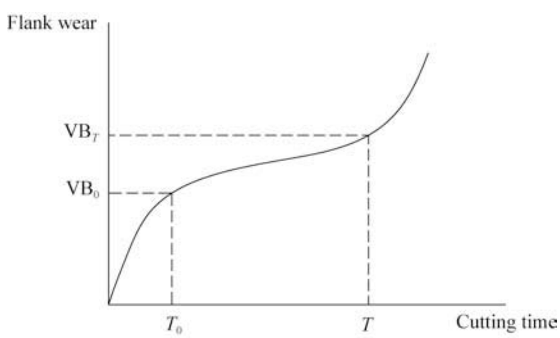

Fig.1 Cutting tool wear variables.

2.1. Comparison of K_0 and K_1

Tool wear data including different machining processes, turning, milling, drilling, etc., are collected from 873 tool wear curves in 227 tool wear figures from 90 articles[2,4-92]. Comparison between K_0 and K_1 is made in each wear curve. The result shows that 800 curves satisfy the relationship that higher WRIWP results in higher WRUWP. It indicates that this relationship is a high probability event in various machining operations such as turning, milling, drilling, etc., in a small sample space.

The comparison result also shows that the probability decreases greatly when the curves are obtained in the tests using various coolant and lubricant. There are 38 such curves in which only 26 curves meet the above rule. The phenomena remain to be further studied.

2.2. Probability distribution of g, K_0 and K

For further study, 172 curves (despite of machining process) with relatively more measuring points and typical process of tool wear are selected from 873 curves, and T_1, VB_1, g, K_0, K_1 and K are calculated, and then the samples are obtained and analyzed (see Table 1).

By Chi-square test, random variables g, K_0 and K followed Weibull, Lognormal and Gamma probability distribution ($g \sim W(0.88,14.19)$, $K_0 \sim LN(-3.46, 1.46)$, $K \sim \Gamma(4.48,0.88)$) respectively, which are shown in Fig.2. Numerical characteristics of probability distribution functions are shown in Table 2.

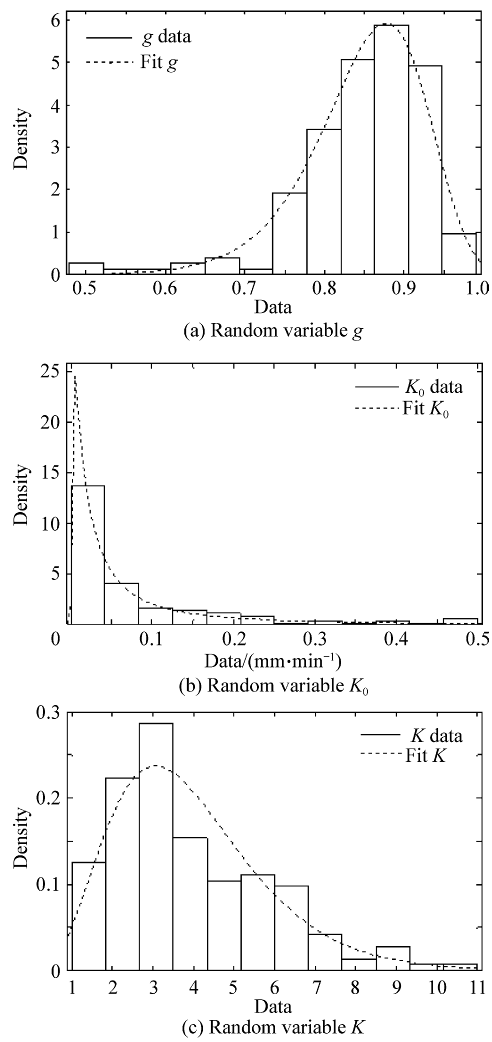

Fig.2 Sample histogram and probability distribution fitting of g, K_0 and K.

The density function of g shows that the probability of the g's value above 0.7 is 0.962 and that above 0.6 even surprisingly reaches 0.996, which demonstrates that tool life is mainly decided by the uniform wear period. In addition, the dispersion coefficients of the samples T_1 and K_1 are 4.9 times and 2.3 times of that of VB_1 respectively. It is easily inferred that, on the grounds of Eq.(4), WRUWP, of the two factors deciding the uniform wear time, is a major one. In a word, tool life mainly depends on WRUWP.

Table 1 Statistical description of sample

Random variable	Size	Minimum value	Maximum value	Average value $\bar{X}$	Standard deviation S	Dispersion coefficient $S/\bar{X}$
K_0/(mm·min^{-1})	172	0.000 6	0.500 0	0.074 7	0.104	1.392 2
K_1/(mm·min^{-1})	172	0.000 1	0.149 3	0.021 2	0.028 6	1.349 1
K	172	1.185 0	10.975 0	3.948 5	1.933 8	0.489 8
g	172	0.500 0	0.972 0	0.848 3	0.082 1	0.096 8
VB_1/mm	172	0.015 0	1.060 0	0.194 2	0.115 2	0.593 2
T_1/min	172	2.000 0	1 819.800 0	51.354 8	149.540 4	2.911 9

Table 2 Numerical characteristics of probability distribution functions

Random variable	Density function	Average value $\bar{X}$	Standard deviation S	Dispersion coefficient $S/\bar{X}$
g	$f(x)=\begin{cases} 0.88^{-14.19}\times 14.19x^{14.19-1}\mathrm{e}^{-\left(\frac{x}{0.88}\right)^{14.19}} & x\ge 0 \\ 0 & x<0 \end{cases}$	0.848 3	0.073 2	0.086 3
K_0/(mm·min^{-1})	$f(x)=\begin{cases} \dfrac{1}{1.46x\sqrt{2\pi}}\mathrm{e}^{\frac{-(\ln x+3.46)^2}{2\times 1.46^2}} & x>0 \\ 0 & x\le 0 \end{cases}$	0.091 2	0.248 7	2.725 5
K	$f(x)=\begin{cases} \dfrac{1}{0.88^{4.48}\times\Gamma(4.48)}x^{4.48-1}\mathrm{e}^{-\frac{x}{0.88}} & x\ge 0 \\ 0 & x<0 \end{cases}$	3.942 4	1.862 6	0.472 5

2.3. Analysis of K_0 and K

Viewing from samples K_0 and K, as $K_{max}/K_{min} = 9.3$ and $K_{0max}/K_{0min} = 877.2$, the range of K_0 is much larger than that of K. And from numerical characteristics of the probability distribution functions of the random variables K_0 and K, as shown in Table 2, the disperse coefficient of K_0 is 5.8 times of that of K. It is therefore demonstrated that the values of K, which distribute within a rather narrow range, fluctuate less than that of K_0. In other words, the values of K are relatively more stable and are less influenced by cutting conditions. So it can be said that statistically there is certain qualitative relationship between WRIWP and WRUWP.

Let K_a and K_b represent K for two different tool materials a and b respectively, then the following probability distribution can be achieved:

$$K_a \sim \Gamma(4.48, 0.88)$$
$$K_b \sim \Gamma(4.48, 0.88)$$

Obviously, K_a and K_b are independent random variables, and then density functions of division of random variables (K_a/K_b) can be obtained:

$$f(K_a/K_b)=\frac{\Gamma(8.96)x^{3.48}}{[\Gamma(4.48)]^2(x+1)^{8.96}} \tag{7}$$

According to Eq.(7), the probability is 0.911 when $0.3\le K_a/K_b\le 3.3$. Therefore, if WRIWP of tool material a is N (it could be valued to 3.3) times higher than tool material b, tool material a would wear faster than tool material b in the uniform wear stage with 91.1% confidence degree. It is therefore reasonable to assess WRUWP by using WRIWP. Comparative analysis of the 172 curves reveals that when N=3.3, there are only 14 curves which do not meet this relationship. If the cutting conditions can be more uniform, the values of K should be more centralized. According to statistical data, the ratio is generally $0.5 \le K_a/K_b \le 2$.

2.4. Tool materials selection

On the basis of the close correlation between WRIWP and WRUWP and the fact that tool life is mainly determined by WRUWP, a methodology to rapidly select suitable tool materials is proposed based on the initial wear. Based on the given cutting condition, the tool materials recommended by tool companies can be selected, which should be the same kind of tool material such as cemented carbide material. Single factor tool wear experiments using various tool materials are designed, and tool life can be assessed by comparison of WRIWP, then suitable tool materials can be selected.

To verify the validity of this new method, a comparative analysis of 81 tool wear curves, with tool wear criteria being 0.2 mm (30 curves) and 0.3 mm (51 curves), is carried out. The results show that when the value of N is 3.3, there is just one curve which does not follow the relationship between WRIWP and tool life. And based on the rapid selection, 29 and 50 curves are eliminated for the 0.2 mm and 0.3 mm criteria respectively, owing to fast WRIWP. Only two curves are selected, which exhibite the longest life in their own spaces. Thus standard tool wear tests can be carried out using the most suitable tool materials, eliminating the time and money consumption to test the tool materials which would be proved unsuitable eventually.

3. Experiments for Tool Materials Rapid Selection

For machining titanium alloy TC4 widely used in aviation field and to select suitable tool materials, 22 tool materials recommended by 14 cutter manufacturers are selected (see Table 3). As shown in Table 3, the unified symbol of insert grade is “xx”, capital letter A, B, C present tool companies, and Arabic numerals mean insert generation from a certain tool company. For example, G2 means the second tool material from G manufacturer. All tool materials in Table 3 are cemented carbide tools with *M* tolerance.

3.1. Experimental set-up

The conditions of these tool initial wear experiments are as follows:

1) Workpiece: TC4 bar, solution-treated and aging.

2) Tool holder, Stellram: MCLNR2525M12-N, SSBCR2525M12, PSBNR2525M12.

3) Lubricant: QUAKERCOOL 370 KLG, 5%-10% water-soluble cutting fluid.

4) Tool geometry parameters: cutting edge angle $\kappa_r = 75°$, the other tool geometry features are provided by the combination of tool holder and tool insert.

5) Cutting speed: 68 m/min.

6) Feed rate: 0.1 mm/r.

7) Depth of cut: 1.3 mm.

3.2. Results and discussion

Experiments are terminated when cutting time is 2 min under each cutting condition. Flank wear VB_0 is measured, and K_0 is calculated (see Table 3). In the present work, *N* is selected to be 2 because of the similar cutting conditions. The suitable tool materials B2, C1, D1, G2, H1, L1 and L2 are selected rapidly through comparison of different values of K_0.

All the tool initial wear experiments last 2 h and consume 0.9 kg TC4. Obviously, compared with standard tool wear experiments, the new method saves time and money.

Table 3 Tool initial wear experimental results

Experiment No.	Insert grade	Tool material	Cutter company	VB_0/mm	K_0/(mm·min^{-1})	Cutting time/min
1-1	CNMG120408-xx	A1	A	0.070	0.035 0	2
1-2	CNMG120408-xx	A2	A	0.065	0.032 5	2
1-3	CNMG120404-xx	B1	B	0.043	0.021 5	2
1-4	CNMG120408-xx	B2	B	0.036	0.018 0	2
1-5	CNMG120408-xx	C1	C	0.027	0.013 5	2
1-6	CNMG120408-xx	D1	D	0.033	0.016 5	2
1-7	CNMG120408-xx	E1	E	0.072	0.036 0	2
1-8	SNMG120408-xx	F1	F	0.077	0.038 5	2
1-9	SNMG120408-xx	G1	G	0.054	0.027 0	2
1-10	SNMG120408-xx	G2	G	0.036	0.018 0	2
1-11	SNMG120408-xx	G3	G	0.058	0.029 0	2
1-12	CNMG120408-xx	H1	H	0.021	0.010 5	2
1-13	SNMG120408-xx	I1	I	0.060	0.030 0	2
1-14	SNMG120408-xx	I2	I	0.070	0.035 0	2
1-15	SNMG120408-xx	J1	J	0.085	0.042 5	2
1-16	SCMT120408-xx	K1	K	0.082	0.041 0	2
1-17	SCMT120408-xx	K2	K	0.085	0.042 5	2
1-18	SCMT120408-xx	L1	L	0.035	0.017 5	2
1-19	SCMT120408-xx	L2	L	0.025	0.012 5	2
1-20	CNMG120408-xx	L3	L	0.048	0.024 0	2
1-21	SCMT120408-xx	M1	M	0.088	0.044 0	2
1-22	SCMT120408-xx	N1	N	0.082	0.041 0	2

Standard cutting tests are implemented on tool materials H1 and L2 chosen from suitable materials, and the results are listed in Table 4. All the cutting conditions but cutting speed are same as those of tool initial wear experiments.

Table 4 Standard experimental results

Tool material	H1	L2
Cutting speed/(m·min^{-1})	83	68
Cutting time/min	70	50
Flank wear/mm	0.170	0.046

According to Table 4, tool materials H1 and L2 show far better wear resistance than that not only recoded in Refs.[93]-[95] but also reported in practical production. Thus it can be said that the new tool materials rapid selection is effective and useful.

4. Conclusions

(1) The relationship between WRIWP and WRUWP is a high probability event with wide range of application in small sample space.

(2) Random variables g, K_0 and K follow Weibull, Lognormal and Gamma probability distribution respectively.

(3) Tool life is mainly influenced by WRUWP.

(4) If the WRIWP of tool material a is N ($2 \leq N \leq 3.3$ is recommended) times higher than tool material b, the WRUWP of tool material a would be very likely faster than that of tool material b, and would have a shorter tool life when the wear criteria are identical.

(5) The tool materials rapid selection method based on the initial wear can be used to primarily select tool materials so as to reduce selection time and cost greatly.

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